Electronics Design for the Fermilab Switchyard Beam Position Monitor System

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Abstract

A beam position monitor system for the Fermilab Switchyard has been developed to measure positions and intensities for 53.1 MHz RF bunched resonant extracted beams of either 1.5 msec or 20 sec duration. The system has a position sensitivity of 100 mV/mm with switching between the fast and slow beam electronics during each machine cycle as needed. For a 1E12 proton beam extracted over 20 seconds the system has a final bandwidth of 10 Hz with a SNR of 45 db. For the same intensity beam extracted over 1.5 msec, a 10KHz bandwidth is maintained with SNR of 70 db.

Design Goals

A 1E12, 53.1 MHz RF bunched resonant extracted beam, extracted over 20 seconds corresponds to a 1000 protons per bunch CW beam, and the same beam extracted over 1.5 ms corresponds to a 1.26E7 protons per bunch CW beam.

Design goals were to measure beam positions to $\pm$ 0.1 mm and beam intensities to a few percent for both, the slow and fast beam spill modes.

From BPM[1] design notes written by R.Shafer we calculate the voltage levels obtainable and the effects of thermal noise on the measurement.

For our cylindrical geometry detectors, the first harmonic of the output voltage, per electrode, for a centered beam is given by

$$V_1 = 2.41 \times 10^{-10}\ Np \text{ volts rms} \qquad (1)$$

Where Np is the number of protons per bunch. The sensitivity of the BPM's are calculated to be

$$(V_a/V_b)\text{db} = .67x \qquad (2)$$

where $(V_a/V_b)\text{db} = 20 \log_{10} (V_a/V_b)$ and x is the distance the beam is displaced from the detector center. Actual measurements show the sensitivity to be about 0.573 db/mm. Differences from calculations are due to crosscoupling effects between detector plates.

The resolution of the detectors is given by

$$S_x = 18.19\ (V_n/V_o)\text{ mm.} \qquad (3)$$

where V_n is the voltage noise and V_o is the detector plate output voltage.

If we assume the noise is due only to thermal noise, then the noise power in a bandwidth ΔB is

$$P_n = 2KT\Delta B \qquad (4)$$

where $K = 1.38\text{x}10^{-23}$ joules/^{o}K
The equivalent noise voltage in a system with characteristic impedance Z_o is

$$V_n = (2KT\Delta BZ_O)^{1/2}\text{volts rms} \qquad (5)$$

Combining equations 1, 3 and 5 we can estimate the ultimate performance of the detectors as

$$S_x = 48.0\ \Delta B^{1/2}/N_p \text{ mm.} \quad (6)$$

Most switchyard detectors are 1-meter long, and tuned to resonate at the RF frequency. They have an average shunt impedance of 9.61K ohms a loaded Q_L of about 190[2]. Tuned detectors will produce about 20 db more signal than untuned detector.

Using equation 6 and taking into account the increase in signal level, for tuned detectors the required bandwidth for $\pm$ 0.1 mm resolution with 1000 protons per bunch is

$$\Delta B = 434 \text{ Hertz}$$

Using equation 3 the SNR needed for $\pm$ 0.1 mm resolution is calculated at 45.2 db.

For fast spill, 1.26E7 protons per bunch, the RF signals from the detector are up by 82 db presenting no problem for resolution. The intensity signals for both types of spill are scaled so 1E12 protons equal 0.5 volts. In our system this provides a 40 db dynamic range.

Electronics

The BPM electronics consists of 3 single width NIM modules per detector. Each set of 3 modules contains electronics for both slow and fast position and intensity measurements. The modules are:

1. RF module.
2. IF module.
3. Intensity and position module.

For slow spill an overall gain of 109 db and a SNR of 45.2 db is needed. While, for fast spill an overall gain of 27 db is required with its final bandwidth of 10 khz. The 10 khz bandwidth was chosen by system constraints.

Position information for both slow and fast spill is obtained using a 90 degree amplitude to phase (AM/PM) converter and a phase detector. The intensity signals are the scaled outputs of the AM/PM converters, converted to a dc voltage by rms to dc converters.

Outputs of the detector are brought to the electronics via 1/2 inch low loss heliax cable. Cables range in length from 200 to 1000 ft and are phase matched to $\pm$ .2 electrical degrees. Attenuations in cable pairs are matched within 0.1 db.

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RF Module

A block diagram of the rf module is shown in Figure 1.

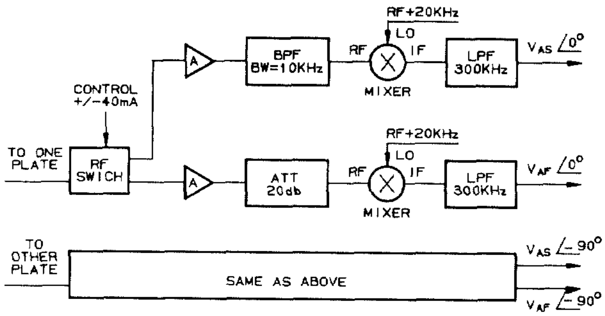

FIG.1 SLOW/FAST SPILL RF MODULE

Signals arriving at the electronics are in phase and switched by an RF switch, with insertion loss of 0.6 db, to the appropriate gain sections. The slow spill signals receive 47 db of amplification and then are filtered by a 10 khz bandwidth band pass filter (BPF), with filter loss of 5.5 db. A mixer, with a conversion loss of 6.5 db and a noise figure (NF) of 7 db, has a local oscillator input equal to the beam frequency plus 20 khz. This LO signal beats with the incoming RF signal to produce an intermediate frequency (IF) of 20 khz. A low pass filter (LPF) removes higher order mixer harmonics. The fast spill rf signals are switched to a 12 db amplifer and then attenuated by 20 db, so as not to overdrive the mixer at higher intensities. An amplifier is used to help preserve the SNR. The rf signals are then mixed to produce the 20 khz (IF) and filtered to remove higher order components.

RF signals arriving from the other plate of the detector receive the same treatment except the local oscillator inputs to the mixer are displaced by 90 electrical degrees. This produces the required phase relationship needed for the AM/PM converter in the IF module.

The overall gain of the RF module for slow spill signals is 33 db and the module has a noise figure of 2.8 db. For the fast spill section the overall gain is -17.1 db and it has a noise figure (NF) of 15db, which will not adversely affect our resolution.

IF Module

The IF module shown in Figure 2 contains different electronics for slow and fast spill. However, both sections use a 90 degree AM/PM converter with a theoretical loss of 3 db.

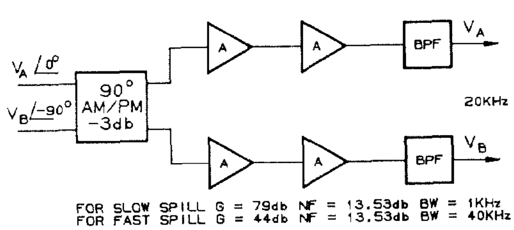

FIG.2 IF MODULE

The AM/PM converter is made up of 3 two way power splitters and one 2 way 180 degree power splitter, as shown in Figure 3.

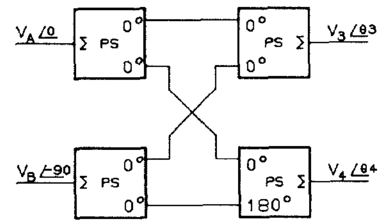

FIG.3 AM/PM CONVERTOR

With input signals 90 electrical degrees apart the output phase difference is given by

$$\theta_3 - \theta_4 = 2 \tan^{-1} (V_B/V_A) \tag{8}$$

The magnitude of the output voltages V_3 and V_4 are calculated by

$$V_3 = V_4 = .5 \ (V_a{}^2 + V_b{}^2)^{1/2} \tag{9}$$

Both AM/PM outputs are amplified and filtered to provide 0.5V for 1 E12 protons of spill. For slow spill the overall module gain is 79 db and the module NF is 13.53 db, with a bandwidth of 1 khz. For fast spill the overall module gain is 44 db, the noise figure is the same as above, the bandwidth is 40 khz.

The overall signal to noise ratio (SNR) of the RF and IF sections can now be calculated. For slow spill the KTB noise power in a 1 khz system is -144 dbm, the detector output signal is -102 dbm yielding a SNR of 42 db. The noise figure of both the RF and IF sections cascaded is 2.81 db giving a final SNR of 39 db. The gain of the cascaded sections is 109 db. For the fast spill sections the overall gain is 27 db and the overall (NF) is 30.55 db. Therefore in a 40 khz system the SNR is 77 db.

Position and Intensity Module

A block diagram of the circuit is given in Figure 4A and 4B

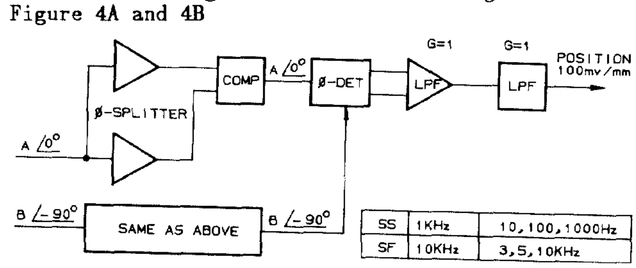

FIG.4A POSITION CIRCUIT

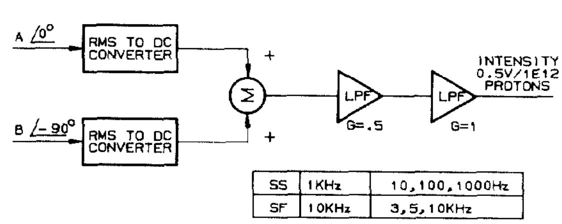

FIG.4B INTENSITY CIRCUIT

This module contains the electronics to produce a dc voltage proportional to the beam position and intensity. The position electronics consists of a phase splitter, voltage comparator, phase detector and low pass filters (LPF) as shown in Figure 4A. The intensity electronics has rms to dc converters and low pass filters as shown in Figure 4B.

Position Circuit

Phase splitters in this circuit help eliminate jitter in the comparator switching at low beam intensity. The comparators are used to eliminate amplitude modulation on the IF signals. A quadurature phase detector provides output voltage proportional to phase differences in the input signals. When the input signals are 90 electrical degrees apart the average value of the phase detectors output voltage is zero. Our phase detectors give about 26.8 mv for each degree of phase difference from 90 degrees. The BPM detector sensitivity is about 0.573 db/mm, corresponding to 3.77 deg/mm of phase shift or about 100 mv/mm of dc position voltage.

We are now ready to estimate the amount of noise therefore, the resolution on the output signal. Since heliax cable has attenuations of 0.5 db/100 ft and our maximum cable length is 1000 ft. worst case attenuation will be 5 db. Adding this attenuation to the SNR at the output of the IF module provides a worst case SNR of 34 db for slow spill and 72 db for fast spill.

Two signals each with a 34 db signal to noise ratio at the input to the phase detector have an effective SNR of 31 db. A 31 db SNR produces a $\pm$ 1.62 degree phase angle excersion at the phase detector outputs. With a phase detector sensitivity of 26.8 mv/deg, $\pm$ 43.4 mv of jitter should appear on the dc output signal for a position uncertainty .43 mm. This signal can be filtered by a switch selectable low pass filter (LPF) with 3 db bandwidths of 10,100,1000 HZ. For a 10 HZ bandwidth a 20 db improvement in signal to noise will be realized giving us 4.34 mv of jitter or .043 mm of uncertainty.

The fast spill signals each with a 72 db SNR have an effective SNR of 69 db at the phase detector inputs. For a SNR of 69 db a resolution of .004 mm would be expected, except further signal processing electronics limit our resolution to $\pm$ 0.1 mm. This signal is also filtered, by a switch selectable LPF with bandwidths of 3,5 and 10 khz. These frequencies were chosen to remove the 20 khz components in the IF signal. Also, in order to see the 1.5 ms fast spill pulses in 0.1 ms the LPF bandwidth must be greater than 3500 HZ.

Intensity Circuit

The intensity circuit is shown by Figure 4B. Signals A and B from the IF module are converted to a dc voltage equal to the RMS value of their magnitudes. The two dc voltages are summed, divided by 2 and filtered by a switch selectable LPF. The intensity channel was scaled in the IF module to provide 0.5V for 1E12 protons of spill. By using outputs of the AM/PM converter to obtain a intensity signal an error in intensity measurement occurs, which is a function of beam position. For a 10 mm shift in the beam a 5% error in the intensity reading will occur; when the beam is on center there is no error from this effect.

Conclusion

The switchyard BPM system was built based on results from beam testing of prototype detectors and electronics. Results from these tests agreed with calculations to within 10% including proton resolution accuracy of $\pm$ 0.1 mm.

Switchyard BPM system consists of 64 tuned detectors; 30 of which see slow and fast spill while the rest see only slow spill. Actual testing of the entire setup will commence the next fixed target run. Preliminary static system checks indicate comparable results can be expected. Variation in the output of electronic packages are within 10%.

Acknowledgments

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References

[1] R. Shafer "BPM Notes" and discussion, guidance and patience.

[2] Q. Kerns et.al., Tuned Beam Position Detectors 1987 Particle Accelerator Conference Session T47, and for his hours on RF theory and techniques.